Case study: deformations of a steep slope excavated in a municipal solid waste landfill

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ABSTRACT
Commencing in autumn 2007, a full scale pilot of landfill mining and reclamation was carried out at the Barrie Municipal Landfill in Barrie, Ontario. This landfill has been in operation for several decades and currently holds in excess of 2 million tonnes of waste. In order to mitigate environmental impacts and provide secure waste disposal for the City, the site is to be "re-engineered", which will involve excavation of approximately 1.5 million m^3 of waste, and screening to segregate fines (largely excess sand that had been used as daily and interim cover). Fines will be stockpiled for use as daily cover for the remainder of the site's operating life. As each area of the landfill is progressively excavated, a base liner and leachate collection system will be installed and the area re-filled with waste. A significant challenge for this project is the lack of space within which to work. According to requirements of the provincial Environment Ministry, temporary slopes are to be no steeper than 3H:1V. Using such grading, however, there would be insufficient space for over 400,000 m^3 of waste during years 2 to 4 of the anticipated 8 years of the project. Accordingly, as part of a full-scale pilot of the landfill mining and segregation process, instrumentation (pneumatic piezometers and inclinometer casings) were installed in an existing 4H:1V slope which was then progressively cut up to 1H:1V as approved by the MOE. Ongoing measurements of lateral displacements and pore pressure were made during steepening of the slope. The displacements were found to be at the low end of the range predicted by a numerical simulation and the slope in this part of the site was determined to be stable.

RÉSUMÉ
En automne 2007, une projet de demonstration ont été effectuées au site d'enfuissment municipal à Barrie, Ontario. Ce projet concerne l'excavation et la segregation des residus et remblai avec compaction pour effectuer un densité supérieur. Le site d'enfuissment a été en fonction pendant plusieurs décennies et se tient actuellement au-dessus de 2 millions de tonnes. Afin atténuer les effets sur l'environnement et pour fournir securité de gestion des déchets, la ville vont effuctuer l'excavation d'approximativement 1.5 million de tonnes avec segregation par écran pour séparer des fines que se compose le sable qui avait été employé comme couverture intérimaire. Des fines seront stockées pour l'usage comme couverture quotidienne pour la durée de fonctionnement de l'enfuissment. Car chaque secteur est progressivement excavé, une barriere et un couche de drainage de lixiviat sera installé et le secteur sera rempli. Un défi significatif pour ce projet est le manque de l'espace dans lequel pour travailler. Selon des conditions du ministère provincial d'environnement, les pentes provisoires sont de n'être pas plus raides que 3H : 1V. En ce cas, il y aurait l'espace insuffisant pour plus de 400.000 m3 des residus pendant les années 2 4 des 8 années prévues du projet. En conséquence, l'instrumentation ont été installées que se compose des piézomètres et inclinomètre dans un pente à 4H:1V qui a été progressivement coupée jusqu'à 1H:1V. Des mesures des déplacements et de la pression d'eau ont été faites pendant l'augmentation de la pente. Les déplacements se sont avérés au bas de gamme de la gamme prévue par une simulation numérique et la pente raide s'est avérée stable.

1 INTRODUCTION

The City of Barrie carried out a Pilot Reclamation and Re-Engineering project at the Barrie (Sandy Hollow) Landfill Site, in order to provide information to assess the costs and issues related to full scale Reclamation and Re-Engineering of the Site. It had previously been determined (GAL, 2007) that excavation of the waste with interim slopes of at least 2(H):1(V) will be necessary in order to open up sufficiently large areas to construct lined landfill cells for the reclaimed materials. This required 2:1 slope is steeper than the 3:1 allowed under the current Certificate of Approval (C of A) issued for the site by the provincial Ministry of the Environment (MOE).

In order to support excavation of the waste to steeper slopes than currently allowed in the C of A, a trial excavation was included as part of the Pilot Reclamation, which was carried out from November 2007 to February 2008, approved by the MOE This paper presents the results of real time field monitoring of deformations and pore pressures as the 20 m high south slope of this landfill was progressively steepened by excavating material from the surface of the slope. Figure 1 shows the progress of excavation and Figure 2 shows an excavated portion of the slope cut to an inclination of 1H:1V. The measured deformations are verified with the results of numerical modelling. Additionally, stability analyses were carried out using the shear strength models provided by various researchers to assess the stability of this cut slope.

2 LITERATURE SURVEY OF SHEAR STRENGTH OF MUNICIPAL SOLID WASTE (MSW)

Comprehensive literature reviews of published values of the shear strength parameters for MSW have been reported by Gharabaghi et al (2008) and Dixon & Jones (2005). From these reviews, three sets of shear strength parameters were selected as representing reasonable values for engineering design and analysis of slopes in Municipal Solid Waste (MSW).

Figure 1. Excavation in progress at the south slope of Barrie landfill.

Figure 2. Slope steepened to 1H:1V

A bi-linear shear strength envelope was proposed by Kavazanjian et al. (1995) and depends on the magnitude of applied normal stresses (σ'). This was determined from back-analysis of existing stable landfill slopes (assumed Factor of Safety, FS = 1.2), together with published data from laboratory testing of recompacted samples. The authors suggest that:

i) for $\sigma' < 30$ kPa, MSW behaves as a purely cohesive material with c' approx. 24 kPa.
ii) for $\sigma' > 30$ kPa, MSW behaves as a purely frictional material with ϕ' approx. 33°.

This model suggests that at the toe of waste slope, "cohesion" associated by interlocking and the presence of tensile reinforcement (associated with fibrous and sheet-like materials) may be a significant factor in contributing to shear strength of MSW, but when normal stress exceeds 30 kPa, cohesion is negligible and the angle of internal friction is approximately 33°. This model is generally considered to be inherently conservative, given that stable slopes were assumed to have a FS of 1.2.

A similar but tri-linear shear strength envelope proposed by Manassero et al. (1996) suggests that:

i) for $\sigma' \leq 26$ kPa, MSW behaves as a purely cohesive material with $c' = 20$ kPa.
ii) for $26 < \sigma' \leq 60$ kPa, MSW is considered a purely frictional material with $\phi' = 38°$.
iii) for $\sigma' > 60$ kPa, it is suggested that $c' = 20$ kPa and $\phi' = 24°$.

A third simple linear failure criteria, (Eid et al, 2000) proposes that c'=40 kPa and ϕ'=35°. This model was developed from large direct shear tests as well as the back-analysis of a failed slope. Relative to Kavazanjian et al. (1995) strength model, this simple linear model predicts higher strength, which is not surprising since it is based, in part, on Limit Equilibrium Analysis of a large failed slope.

Table 1, presents a summary of published shear strength parameters. It is evident that there is considerable scatter in these values. The average of the minimum and maximum reported values are, however, reasonably consistent with the three models discussed above. The "cohesion intercept" c' (associated mostly with the reinforcing effect of fibrous and sheet-like reinforcing materials) may be characterized by averages of the minimum and maximum values = 22 and 25 kPa respectively. Similarly, for the angle of shearing resistance, ϕ', the average of the minimum and maximum values are 29 and 35°.

3 APPROACH

3.1 Field monitoring

Two boreholes (BH-1 and BH-2) were drilled at the anticipated location of the crest of the planned excavation in order to obtain information regarding waste depth, character and leachate pore pressure. Inclinometer casing and pneumatic piezometers were installed in these boreholes. The piezometers were placed at depths selected on the basis of observations made during drilling (saturated zones, etc). Deformations were measured by using a RST digital inclinometer system which is comprised of a digital inclinometer probe, cable system, reel with a battery power and a window pocket PC that functions as a readout, analysis and data storage device. Continuous measurements of pore pressures and deformations were recorded over the period from November 2007 to February 2008.

3.2 Numerical modelling

The pre-failure stress-deformation behaviour of MSW has been modelled using a non-linear elastic hyperbolic constitutive model (Singh et al. 2008). This model has been used in this study to verify deformations observed during real-time monitoring of the cut slope using a finite element software SIGMA/W of GeoStudio 2007(GeoSlope International). The parameters of this model are specific to MSW and have been discussed in detail by Singh et al. (2008). The lower and upper bounds of these parameters were used to obtain range of anticipated lateral deformation at this site as the slope was steepened.

Table 1: Shear strength parameters of MSW from published literature

Reference	Strength Parameter c' (kPa)	Strength Parameter φ'(°)	Method of estimation
Cowland et al. (1993)	10	25	Back analysis of deep trench cut in waste
Caicedo et al. (2002)	67	23	Large DS, pressure phicometer
Edincliler et al. (1996)	27	42	DS
Eid et al. (2000)	25	35	Large DS and also back calculation from four failed slopes
Gabr & Valero (1995)	17	34	Small CU triaxial (values at 20% axial strain
Grisolia et al. (1995)	2-3	15-20	Large Triaxial (at 10-15% axial strain)
	10	30-40	
Harris et al. (2006)	9-14	20-29	DSS, DS, Large CU triax
Houston et al. (1995)	5	33-35	Large DS on undisturbed samples
Jessberger and Kockel (1995)	0	31-49	Both large and small Triaxial
Kavazanjian et al. (1995)	24	0	For normal stress < 30 kPa
	0	30	For normal stress > 30 kPa
Landva & Clark (1990)	0-23	24-41	DS
Landva & Clark (1986)	10-23	24-42	DS on waste from various canadian landfills
Mahler & De Lamare Netto (2003)	2.5-4	21-36	DS
Mazzucato et al. (1999)	43	31	Large DS
Pelkey et al. (2001)	0	26-29	Large DS
Siegel et al. (1990)	0	39-53	DS. At 10 % shear disp. and cohesion assumed zero
Stoll (1971)	0	24-42	Small triaxial
Vilar & Carvalho (2002)	39.2	29	At natural water content
	60.7	23	Saturated sample
Whitian et al. (1995)	10	30	Large DS
Zekkos et al. (2007)		36-41	CU
Zwanenburg et al. (2007)		35-37	Large Triaxial
Average (low-high)	**22-25 kPa**	**29-35°**	

Note: DS- Direct Shear test, CU- Consolidated undrained triaxial test

Published data on the unit weight of MSW indicate a non-linear relationship between the unit weight and the effective confining stress (Zekkos et al., 2006, Kavazanjian et al. 1999). However, for simplicity the stress-deformation analyses conducted in this study considers a constant unit weight of 12.5 kN/cum for MSW, which is typical of most landfills with average compaction. The Young's modulus of elasticity has also been observed to increase with depth and increasing confining stress (Singh and Fleming 2008, Beaven and Powrie 1995). Accordingly, a power function first proposed by Janbu (1963) for a wide range of geo-materials is used which is given by:

$$E = KP_a \left[\frac{\sigma'_3}{P_a} \right]^n \tag{1}$$

where E is Young's modulus of elasticity, P_a is the atmospheric pressure used for normalization of above equation, σ'_3 is effective confining stress and K and n are the model parameters for a non-linear elastic hyperbolic model of MSW.

A maximum horizontal displacement of the waste slope on the order of 150 mm was expected, as the slope was steepened from 4H:1V to 1H:1V, based upon the results of a Finite Element analyses of the cut slope using parameters shown in Table 2. Significant deviation in displacement (as observed from inclinometer data) from this expected behaviour would represent a trigger to cease steepening of the slope. The slope stability analyses were based on Mohr-Coulomb failure criterion.

Table 2. Parameter of hyperbolic model of MSW used in finite element analysis of cut slope

	K	n	Rf
Upper bound	58	0.88	0.82
Lower bound	36	0.61	0.65

4 RESULTS & DISCUSSION

Real-time monitoring was conducted using inclinometers placed at the crest of the slope of existing landfill and deformations were monitored as the slope was steepened by cutting. No significant lateral movement was observed and the slope remained stable even at 1H: 1V. A maximum horizontal displacement of 50 mm was observed in the waste slope. This was less than the expected deformation (130 to 250 mm) based upon the results of Finite Element analyses of the cut slope. Such small deformations likely reflect the effect of large proportion of granular sandy material in the waste, which would tend to make the material stiffer.

Figures 3 and 4 show the results for selected monitoring at BH-1 and BH-2. The apparent movement below 20 m depth in Figures 3 and 4 likely reflects a combination of error (at low displacements corresponding to the precision of the monitoring system) and some small movement of the inclinometer casing within the borehole, which had been drilled to a larger diameter, leaving an open annular space which had partially squeezed or sloughed in, thus precluding backfilling. This effect can be seen by the apparent upslope deformation at approximately 20 m depth (the location of the toe of the slope). This is attributable to the fact that the inclinometer casing itself has some bending stiffness and that immediately below the lowest zone of downslope movement, the casing would tend to bend up-slope, particularly given the presence of a gap between the borehole wall and the outside of the inclinometer casing. Notwithstanding this, it is evident that consistent, but minor downslope movement may be seen from approximately 17 m depth to surface.

The potential presence of a weak zone, which might control the stability of the cut slope and reduce the global FS was considered possible and would also have been detected through monitoring of the inclinometers. Rather than a reasonably "smooth" or C-shaped deformation pattern shown by the inclinometer data (with small but measurable horizontal deformations), the presence of a zone or layer of weaker material would manifest itself as a "kink" in the inclinometer traces as evident from figures 3 and 4. Such weaker zones are consistently less stiff, as has been shown by Singh et al. (2007a) in a parametric study of a four-component model of MSW.

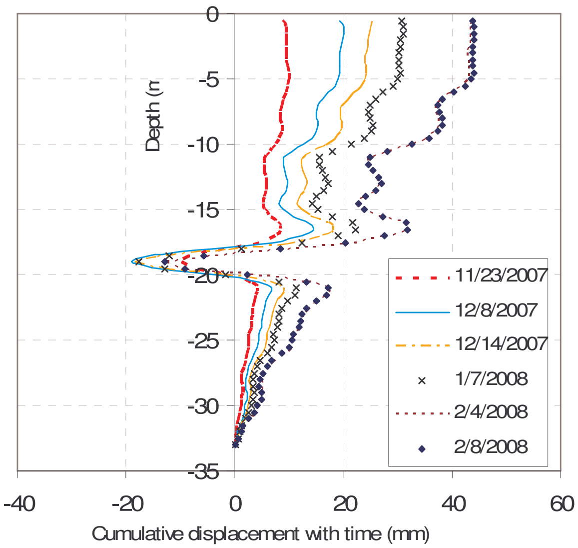

Figure 3. Lateral displacements measured at BH-1

An evaluation of waste slope stability (Limit Equilibrium Analyses) of this cut slope was carried out using Slope/W software of GeoStudio 2007 (GSI, 2007). The conservatively low shear strength parameters of Kavazanjian et al, (1995) provided a lower bound estimate of the factor of safety (as these parameters are based upon stable slopes), whereas the shear strength parameters proposed by Eid et al, (2000), which are based on an actual failure, provided the highest estimates for the factor of safety for this cut slope (Table 3).

Based upon the studies cited above, as well as recent work from University of Saskatchewan, including waste samples from Toronto's Brock West Landfill (Singh et al. 2007) and Saskatoon's Spadina Landfill (Singh et al 2008), a reasonable, although conservative estimate for the shear strength parameters of MSW is c'=20 kPa, ϕ'=32°. Based on the stability analysis noted above, the estimated factor of safety under such an assumption is 1.58 for a slope 20 m high at 1H: 1V with no pore pressure.

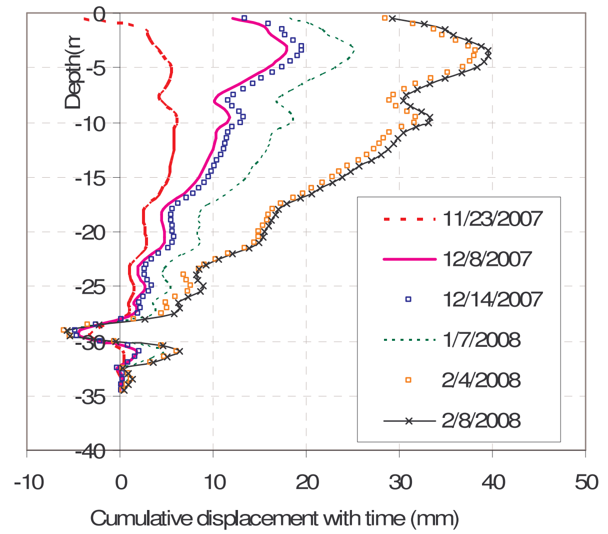

Figure 4: Lateral displacements measured at BH-2

Table 3. Estimated FS of cut slope

Shear strength model	Estimated FS
Kavazanjian et al.(1995) c' = 24 kPa, ϕ' = 0 (for σ' < 30 kPa) c' = 0, ϕ' = 33° (for σ' > 30 kPa)	FS = 1.00
Manassero et al. (1996) c' = 20 kPa, ϕ' = 0 (for σ' < 26 kPa) c' = 0, ϕ' = 38° (for 26 kPa <σ' < 60 kPa) c' = 20 kPa, ϕ' = 24° (for σ' > 60 kPa)	FS = 1.24
Eid et al. (2000) c' = 40 kPa, ϕ' = 35°	FS = 2.15
Values selected on the basis of Table 2 c' = 20 kPa, ϕ' = 32°	FS = 1.58

5 CONCLUSIONS

The review of the current literature regarding the strength of waste and the stability of waste slopes was carried out and it was concluded that MSW is stable at steeper slopes than 3:1, up to as much as 1:1. This was verified at the Barrie Landfill in the course of a carefully planned and executed temporary steepening of an instrumented section of the south slope of the Barrie Landfill.

The low magnitude of observed displacements confirms that only a small portion of the shearing resistance of the waste had been mobilized (i.e. high FS) pointing towards the existence of high angle of shearing resistance of MSW. This observation is well substantiated with the results of slope stability analysis as well as physical evidence of cut slope observed in this study.

The assessment of slope stability in waste is site specific owing to the heterogeneous and changing characteristics of waste during decomposition. It is cautioned that a qualified engineer should assess the stability of waste slopes on the basis of experience, judgment and observation of local waste characteristics.

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